HIGH POWER INVERSE PINCH SWITCH

Gregory L. Schuster and Ja H. Lee
NASA Langley Research Center
Hampton, Virginia 23665

and

Sang H. Choi
Information & Control Systems, Incorporated
Hampton, Virginia 23669

Abstract

In high power switches the "z-pinch" phenomenon greatly accelerates deterioration of the switch. This "z-pinch" phenomenon is caused by the $\vec{J}x\vec{B}=\vec{F}$ force that results in current sheet compression. The pinched current column with a high current density on a small area of the electrodes (hot spot) causes the electrodes to evaporate and damage, thus changing the characteristics of the switch. The design of an inverse "z-pinch" switch not only eliminates the z-pinch effects but utilizes $\vec{J}x\vec{B}$ for reducing the current density. A prototype of the inverse pinch switch with plasma puff triggering has accumulated hundreds of runs for performance tests. Pictures of the switching discharge taken with an image converter camera (I.C.C.) show the discharge to be nearly axi-symmetric. Fast streak pictures made in microseconds show the discharge travelling radially outward as expected. Electrical probe measurements indicate that continued improvement of this basic geometry should prove the switch capable of higher coulomb transfer and with many other advantages over a conventional spark-gap switch.

Introduction

High power switches are necessary in a number of applications, including excitation of pulsed high energy lasers, generation of energetic particle beams, and magnetoplasmadynamic thrusters.

At the present time, spark gap switches are the only devices capable of switching powers greater than 10^7 kV-A (see fig. 1). However, these high power switches have a relatively short lifetime (see fig. 2). The figures are based on the survey reported in [1].

The short lifetime of these switches is due to electrode heating (from which electrode erosion follows). Local electrode heating is proportional to the current density squared $J^2 = I^2/A^2$, where I is the total current carried through the area A of the electrode surface. Since high current I is necessary for high power applications, the only possible way to lower the current density is to increase the active electrode area engulfed by the current column. This is difficult to achieve in conventional spark-gap switches due to a ponderomotive force $\vec{F} = \vec{J} \times \vec{B}$ that constricts the current column to a small area of hot spots (see fig. 3). With the inverse pinch switch[2], however, the ponderomotive force is utilized to spread the current column over a larger area, thus reducing the current density.

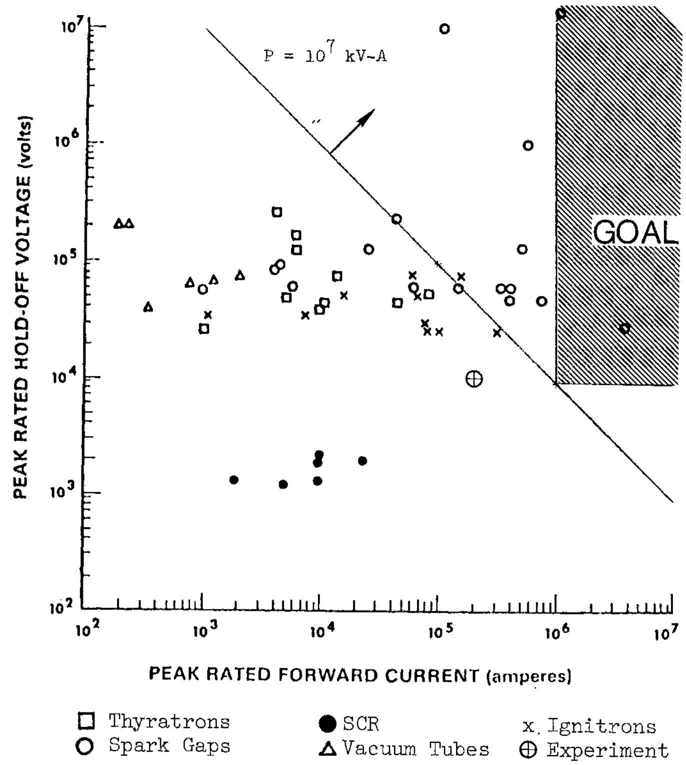

Figure 1 Peak rated hold-off voltage vs. peak rated forward current. Spark Gaps are the best switches for transferring powers greater than 10^7 kV-A.

A prototype of the inverse-pinch switch has been constructed for experimental evaluation. A schematic of the switch is shown in figure 3. The basic principle that makes this switch unique is the fact that part of the cathode is located concentrically within the anode. Hence, current is flowing in two directions where breakdown occurs. This geometry directs the ponderomotive force radially outward, spreading the current column over a larger active area (rather than collapsing it).

Experimental Apparatus and Diagnostics

The experimental apparatus and diagnostics are shown in figure 4. The capacitor bank consists of

Report Documentation Page			*Form Approved* *OMB No. 0704-0188*

1. REPORT DATE **JUN 1985**	2. REPORT TYPE **N/A**	3. DATES COVERED **-**
4. TITLE AND SUBTITLE **High Power Inverse Pinch Switch**		5a. CONTRACT NUMBER
		5b. GRANT NUMBER
		5c. PROGRAM ELEMENT NUMBER
6. AUTHOR(S)		5d. PROJECT NUMBER
		5e. TASK NUMBER
		5f. WORK UNIT NUMBER
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) **NASA Langley Research Center Hampton, Virginia 23665**		8. PERFORMING ORGANIZATION REPORT NUMBER
9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)		10. SPONSOR/MONITOR'S ACRONYM(S)
		11. SPONSOR/MONITOR'S REPORT NUMBER(S)

12. DISTRIBUTION/AVAILABILITY STATEMENT
Approved for public release, distribution unlimited

13. SUPPLEMENTARY NOTES
See also ADM002371. 2013 IEEE Pulsed Power Conference, Digest of Technical Papers 1976-2013, and Abstracts of the 2013 IEEE International Conference on Plasma Science. Held in San Francisco, CA on 16-21 June 2013. U.S. Government or Federal Purpose Rights License.

14. ABSTRACT
In high power switches the "z-pinch" phenomenon g reatly accelerates deterioration of the switch. This ~'z-pinch" phenomenon is caused by the ~=F force that results in current sheet compression. The pinched current column with a high current density on a small area of the electrodes (hot spot) causes the electrodes to evaporate and damage, thus changing the characteristics of the switch. The design of an inverse "z-pinch" switch not only eliminates the z-pinch effects but utilizes ~x~ for reducing the current density. A prototype of the inverse pinch switch with plasma puff triggering has accumulated hundreds of runs for performance tests. Pictures of the switching discharge taken with an image converter camera (I.C.C.) show the discharge to be nearly axisymmetric. Fast streak pictures made in microseconds show the discharge travelling radially outward as expected. Electrical probe measurements indicate that continued improvement of this basic geometry should prove the switch capable of higher coulomb transfer and with many other advantages over a conventional spark-gap switch.

15. SUBJECT TERMS

16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT	18. NUMBER OF PAGES	19a. NAME OF RESPONSIBLE PERSON
a. REPORT **unclassified**	b. ABSTRACT **unclassified**	c. THIS PAGE **unclassified**	**SAR**	**4**	

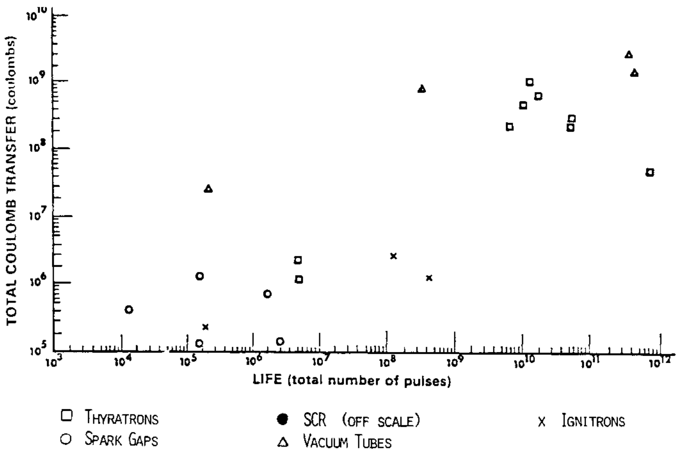

Figure 2 Total Charge Transfer Capability vs. Life of Switch. The high power spark gaps have the lowest number of total pulses.

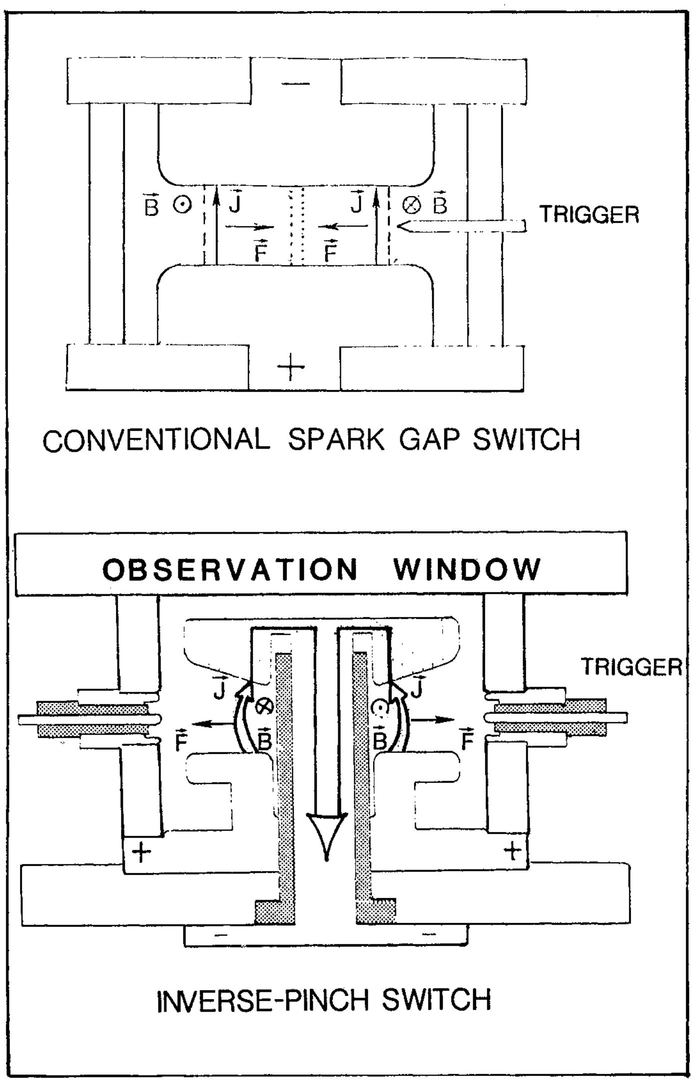

Figure 3 In high power switching, the ponderomotive force $\vec{F}=\vec{J}x\vec{B}$ plays a predominant role. For the conventional spark-gap switch the pondero-motive force collapses the current column. With the Inverse-pinch switch, however, the ponderomotive force acts in the opposite direction.

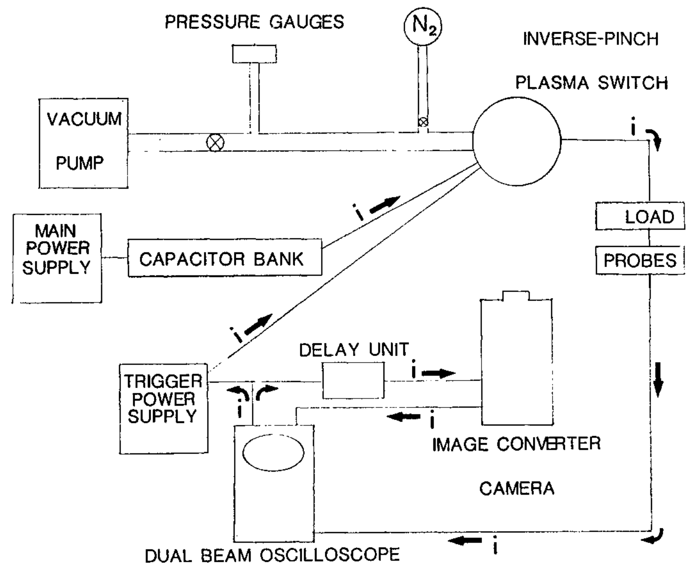

Figure 4 Experimental Apparatus and Diagnostics

three 1.97 µF capacitors in parallel for a total measured capacitance of 5.92 µF. The capacitors use castor oil for a dielectric and may be charged up to 60 kV. The main power supply is only capable of charging the bank up to 25 kV, however. The trigger power supply sends a 20 kV pulse to the trigger mechanism in the switch. An image converter camera with exposure times 20 ns in the frame mode and 5 µs, 10 µs, 20 µs or 50 µs in the streak mode was used to observe the emission from the current sheet. The trigger delay generator is used to delay signals from 0 to 10 µs.

The electrical parameters of the circuit are obtained from Rogowski coils and voltage dividers. The Rogowski coil is accurate to 30 percent when the discharge frequency is greater than 95 kHz. The voltage divider has a X2600 attenuation. The vacuum pump is used to evacuate the switch chamber pressure down to 2 µmHg.

The Experimental Operation

The operation of the experiment can be summarized briefly. High voltage is applied across the 5.92 µF capacitor bank shown in figure 4 and the stored energy is discharged to ground through the switch when triggered. Typical power transfers are of the order of 10^6 kV-A. A mechanical and diffusion pump system is used to reduce the switch chamber pressure to 2 µmHg, before the filling of the switch chamber with controlled pressures of nitrogen.

The ICC faces the observation window shown in figure 3. A series of holes have been drilled through the cathode allowing the camera to "see" the plasma and the current sheet motion. A signal is sent from the oscilloscope to initiate the trigger pulse generator for switch closing and the camera delay unit for controlled photography. By adjusting the delay time on the camera delay unit (usually 0-5 µs) various states of the discharge were captured on film. In the frame mode, the ICC takes three pictures at successive times with a 20 ns exposure time. These pictures reveal the emission from the current sheet in the switch (see fig. 5).

The camera may also be operated in a "streak" mode. When operating in the streak mode, the entire

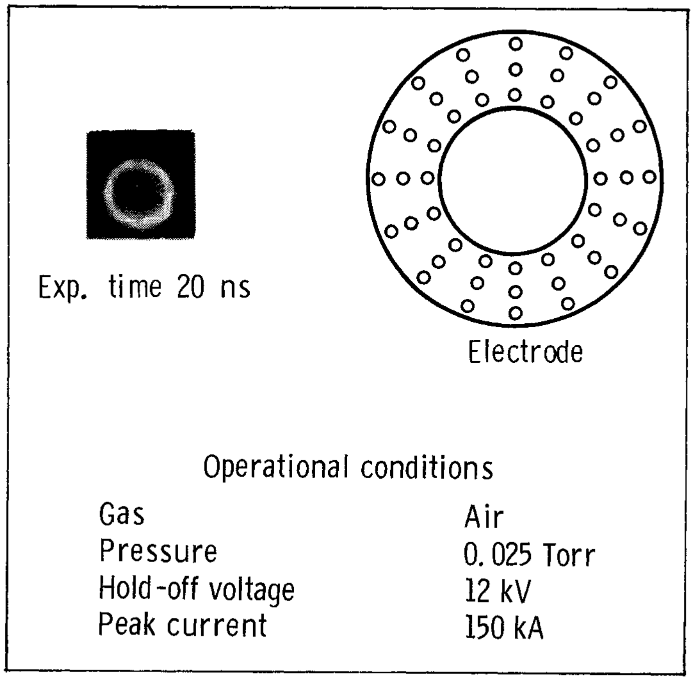

Figure 5 Frame photograph exhibiting the uniformity of the breakdown.

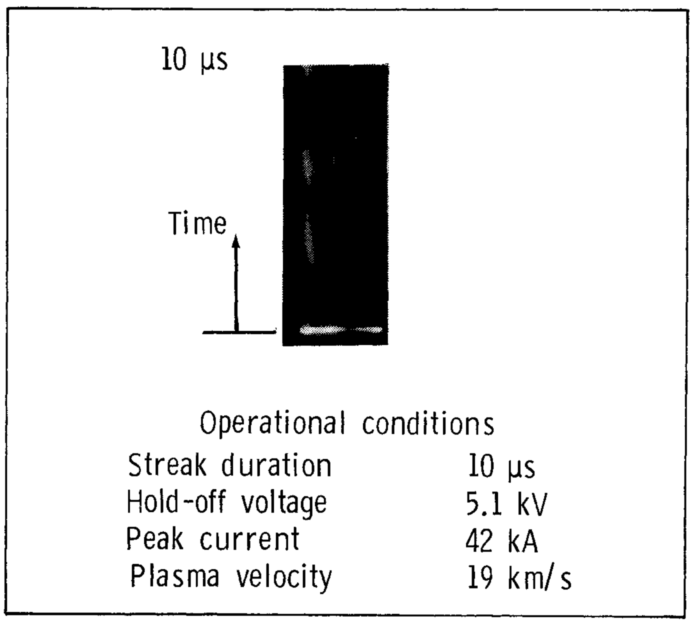

Figure 6 Image Converter Camera photograph showing radially diverging current column.

front face of the switch is masked off with dark tape except for a small 1 mm wide horizontal slit. The camera then effectively takes smeared pictures of this slit and displaces them along the vertical axis of the filmback. Hence, the vertical axis of the picture is essentially a time scale. This is very useful in determining the direction that the plasma is traveling (radially inward or outward) as well as permitting a rough estimate of the velocity of the plasma. From the streak photograph of figure 6, it is clear that indeed the discharge is traveling radially outward.

The electrical parameters of the switch circuit are generally measured using the Rogowski coil[3]. Basically, a Rogowski coil is a solenoid bent into the shape of a torus. When this coil is coupled with an RC integrating circuit, its output voltage is related

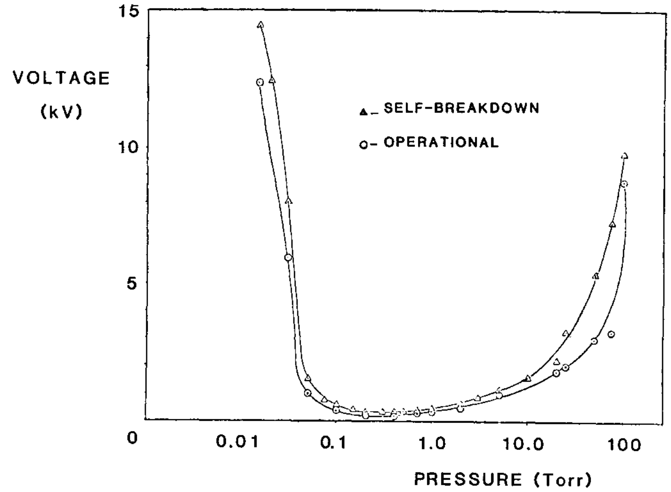

Figure 7 Hold-off Voltage vs. Chamber Pressure for prototype inverse pinch switch. Note that the switch exhibits a "Paschen" curve behavior as expected.

linearly to the switching current. By using the capacitor charging voltage and the peak current measured from the Rogowski coil signal, the switch performance may be rated with a single parameter $P = V \times I$. For a charging voltage of 10 kV, we measured a peak current of 200 kA resulting in $P = 2 \times 10^6$ kV-A. This is indicated by ⊕ in figure 1 for comparing to other spark gap performance. Measurements were made with frame photographs, streak photographs, voltage and current signals at various switch chamber pressures. Varying the chamber pressure has an effect on the maximum hold-off voltage as shown in figure 7. The switching characteristics have been studied for various pressure at voltages slightly less than the maximum hold-off voltages for the pressure.

Results and Discussion

Frame Photographs

Figure 5 shows frame photographs of a discharge taken through the perforated cathode during switching. As mentioned earlier the cathode was perforated so that the current column behind it could be visible. Such frame photographs show the degree of uniformity of the discharge. Some problems have been encountered occasionally while attempting to obtain a uniform discharge. The frame photos revealed that the discharge is often initiated on one side of the cathode and subsequently grows to the other side as time passes.

It is possible that this problem is caused by the trigger mechanism. Ionization in the switch gap is caused by a high-voltage pulse applied across the trigger plates (fig. 3). If the trigger mechanism does not break down axisymmetrically, the gas ionizes asymmetrically and the switch breakdown cannot be uniform. Indeed, photographs of the trigger mechanism in operation show that the trigger breakdown is not always axisymmetric. However, most of the time we obtained a relatively uniform main breakdown as shown in figure 5.

Streak Photographs

Streak photographs taken with the ICC camera show radial plasma motions in the switch. The operation of the inverse pinch forces was clearly indicated in the streak photographs. As shown in figure 6, almost all

of the pictures show that the current sheet in the switch is radially diverging as expected. Note that the secondary current sheet due to the ringing of the circuit also behaves similarly. The radial velocity of the plasma may also be obtained from these photographs by measuring the displacements in space and time.

Once the velocity is known, it can be compared with the results from the numerical simulation based on a snowplow model.

Snowplow Model: In figure 8, the velocities of the current sheet at various vacuum pressures (described as densities in the figure) versus hold-off voltages or peak currents are plotted. The blank squares, circles, and triangles in the figure are the velocities which were obtained from the streak photographs. Note that the velocities are widely spread even when the switch operates at the same density and achieves approximately same peak currents. This is probably due to errors which come from the resolution and sensitivity of the streak mode pictures as well as errors in measurement of such parameters as vacuum fill pressures and hold-off voltages. The solid squares, circles, and triangles in the figure are the velocities which were calculated by the simulation code [4] using the hold-off voltages, peak currents and ringing frequencies measured in the experiment. Hence, the calculated velocities show the same tendency of spread. In general, both results show the fact that the velocities, both from experiments and calculation, are within agreement and have the same tendency following the theoretical values which are shown as solid lines in figure 6.

Current Density: The streak photograph is also useful in finding the active anode area which is necessary for estimating the current density. When a horizontal line is ruled across the streak photograph of figure 6 one can measure the width of the electrodes that the current sheet is occupying (on this line) at this instant. When the discharge is uniform, this average width $\bar{\ell}$ may be multiplied by the mean circumference $\bar{r}$ to obtain the effective electrode area

$$A_{effective} = 2\pi \bar{r}_{effective} \bar{\ell}_{effective}$$

The peak current density is then given by

$$\vec{J}_p = \frac{\vec{I}_p}{A_{effective}}$$

The magnitude of $\vec{J}_p$ is very important, since the heating of the electrodes is related to J^2. The heat generated per unit area, H, is $H = J^2 R t$ where P is resistance of the current column and t is the heating time.

A typical current density achieved in the experiment for the inverse pinch switch is

$$J_p = \frac{42kA}{43\ mm^2} = 980\ \frac{A}{mm^2}$$

For a conventional spark-gap switch of the same current, the current column will collapse to a 2 mm diameter area, yielding a current density of

$$J_p = \frac{42kA}{3.14\ mm^2} = 13,400\ \frac{A}{mm^2}$$

The above computations show that the inverse-pinch switch, has reduced the current density by 1 order of magnitude. Since the heating is related to J^2, the heating is reduced by 2 orders of magnitude. This translates directly to longer switch life, since heating is the phenomena responsible for electrode erosion. Also, in the conventional spark-gap switch the current column is static while the current sheets travel in the inverse-pinch switch. Since the heating of the electrode is also related directly to the time the column remains in one spot, the switch lifetime improvement may be much greater than 2 orders of magnitude.

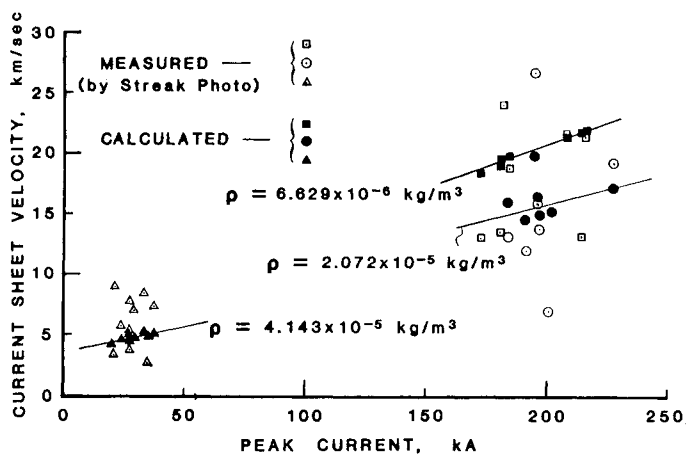

Figure 8 Current Sheet Velocity vs. Peak Current

The lifetime of the switch has been very good for preliminary tests. Many hundreds of breakdowns have been initiated and the electrodes still show no trace of erosion. The main problem is finding an insulating material that will adequately hold-off the potential difference between the anode and cathode. This has been the major source of switch "down-time" in the lab. An improved insulator design and use of new material give good promise and a lifetime test is currently being carried out.

Conclusions

The prototype inverse pinch switch tested in the laboratory has been successful in reducing current density and dispersing the current column over a large electrode area (as compared to conventional spark-gap switches). Evidence of this is supported by frame and streak photographs taken by an image converter camera. This dispersion of the current column with a reduced current density promises the switch lifetime improvement of > 2 orders of magnitude and a significantly greater current transfer capability.

References

[1] H. B. Odom, et al., "High Power Switch Capabilities" in Energy Storage, Compression, and Switching, V. Nardi et al. (eds.), Plenum Press, NY, 1978, p. 987.

[2] J. H. Lee and S. H. Choi, "A Surface Discharge Triggered Inverse-Pinch Switch," Presented at the APS Plasma Physics Division Meeting, MA, Oct. 29-Nov. 2, 1984.

[3] S. L. Leonard, "Basic Macroscopic Measurements" in Plasma Diagnostics Techniques, R. H. Huddlstone and S. L. Leonard (eds.), Academic Press, NY, 1965, pp. 8-13.

[4] S. H. Choi, "Simulation Study of a New Inverse-Pinch High Coulomb Transfer Switch," Final Report, NASA Contract number NAS1-17488, Information & Control Systems, Inc., Hampton, VA, May 1984.